

# High Energy Double-pulsed Ho:Tm:YLF Laser Amplifier

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## ABSTRACT

A high energy double-pulsed Ho:Tm:YLF 2- $\mu$ m laser amplifier has been demonstrated. 600 mJ per pulse pair under Q-switch operation is achieved with the gain of 4.4. This solid-state laser source can be used as lidar transmitter for multiple lidar applications such as coherent wind and carbon dioxide measurements.

## INTRODUCTION

Solid-state 2- $\mu$ m laser has potential for multiple lidar applications to detect water vapor, carbon dioxide and winds [1-3]. An efficient, single frequency 2- $\mu$ m laser is also an ideal pump source for an optical parametric oscillator (OPO) and an optical parametric amplifier (OPA), which can be tuned over the mid-IR wavelength region for medical and remote sensing applications. A traditional 2- $\mu$ m laser is operated at single pulse output per pump pulse. However, a Ho and Tm based 2-micron laser can also be operated in double-pulse fashion to take advantage of the long lifetime of Ho laser excited state and the extended Tm-Ho energy sharing process to utilize the pump energy efficiently [4]. A unique feature of this laser is that it provides two Q-switched pulses with a single pump pulse.

To achieve higher output energy from a 2-micron laser while maintaining a high beam quality, a master-oscillator-power-amplifier (MOPA) is desired. We have previously developed a side pumped power amplifier system and demonstrated a 600-mJ-output energy [5]. The amplifier system consisted of four side-pumped amplifiers with total pump energy of 28 J. Although the output energy was high, the overall optical-to-optical efficiency was only 2%. Since the first two amplifiers were not operated in the saturation region, they yielded 1% optical-to-optical efficiency.

In this paper, we describe a double-pulsed Ho:Tm:YLF laser amplifier. By operating the laser in a double-pulse format, the residual energy stored in the Tm atoms will repopulate the Ho atoms that were depleted by the extraction of the first Q-switched pulse. Thus, the otherwise wasted energy is utilized. In addition, the laser crystal doping concentrations have been optimized and the amplifier is operated in a region close to saturation. All these factors contribute to achieve higher amplifier efficiency.

## DOUBLE-PULSED AMPLIFIER RESULTS

Ho:Tm:YLF has a complicated physics associated with the pumping process and excitation dynamics. It is well known that in a Ho:Tm system the Tm absorbs pump energy and through a non-radiative process transfers energy to the active ion, Ho [6]. Figure 1 shows the dynamic character of the Ho upper laser level population in the pumping and lasing period. The pump pulse width for the laser is typically 1ms. The Ho upper laser level population increases with the pump pulse. It reaches the maximum about 100  $\mu$ s after the pump pulse is terminated. At this moment, a first Q-switched pulse is obtained which extracts the energy stored in the Ho upper laser level  $^5I_7$ . Since a typical Q-switched pulse width is much shorter than the equilibrium time between the Tm  $^3F_4$  and Ho  $^5I_7$  manifolds, a sharp

decrease in the population of Ho upper laser level  $^5I_7$  takes place [8]. However, the energy stored in Tm upper level  $^3F_4$  is relatively intact during the first Q-switch pulse. As a result, only the energy stored in Ho participates in the laser action. Even though the pump pulse no longer exists during this moment, a new equilibrium between the Tm  $^3F_4$  and Ho  $^5I_7$  manifolds is again established by the Tm and Ho energy sharing process. Thus, a significant fraction of the energy stored in Tm can also be used in laser action, resulting in high overall laser efficiency. After certain time interval, typically about 200  $\mu$ s, the Ho upper laser level  $^5I_7$  is again populated and the second Q-switch pulse can be generated.

The experimental measurement of the Ho upper laser level  $^5I_7$  population dynamics obtained by pump-probe method agrees well with the simulated calculation as shown in Fig. 1. The optimum Q-switch time for the second Q-switch pulse was determined by adjusting time interval of the two Q-switch pulses while monitoring the overall output energy.

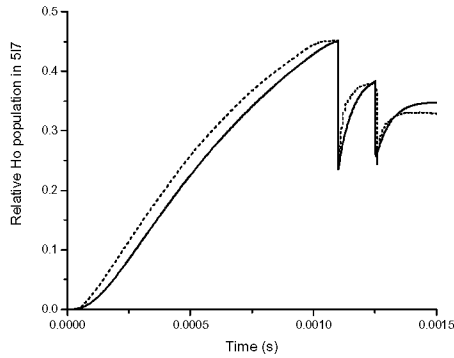


Fig. 1. Relative Ho upper laser level population during the pumping and lasing period. The pump pulse started from 0 and has a pump width 1 ms. The solid curve represents simulation result and the dashed line is experimental measurement.

The pump module design for the oscillator and amplifiers is similar to that described in detail previously. [7]. Two diode-pumped amplifiers form a chain to provide the necessary gain to the probe beam, which is the output of the oscillator. The YLF laser amplifier rod has a Ho doping concentration of 0.6%, and Tm doping concentration of 6%. The doped section has a length of 40 mm, based on the consideration of providing maximum gain along the a-axis of the laser rod, while avoiding amplified spontaneous emission. The ends of the laser rods are diffusion bonded to two

undoped YLF rods. The rods are pumped by 20 diode arrays, each providing a peak power as high as 360 W. The laser diode arrays and laser rod are both cooled with a coolant temperature set at 15°C.

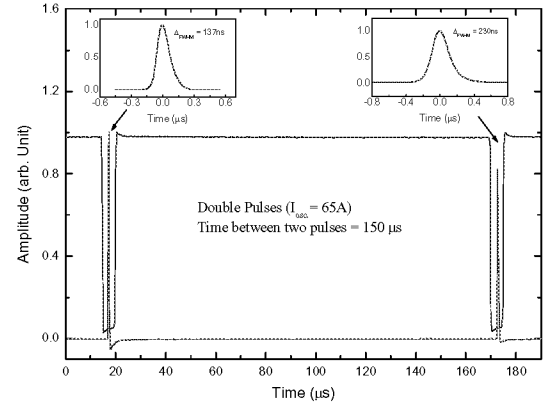


Fig. 2 Double-pulsed amplifier waveform

The waveform pair of Q-switched pulses is depicted in Fig. 2. In this case, the time interval between the first pulse and second pulse is 150  $\mu$ s, and the first pulse has more energy than that of second one. The pulse width of the second pulse is much wider due to longer pulse build time. However, the energy distribution of this pair of pulses can be adjusted by controlling the Q-switch trigger sequence. If the first pulse is generated shortly after the pump, more energy remains for the second pulse, while the period between the two pulses is fixed. In some Differential Absorption Lidar (DIAL) applications, it may be desirable for the two pulses to be at different energies; for example, the energy at on-line wavelength can be larger than that at off-line wavelength. This can be accomplished by delaying the first Q-switched pulse until the maximum gain is available in the laser medium.

The amplifier performance depends on pump density of the probe energy as well as the Ho, Tm doping concentrations. Fig. 3 shows the amplifier output energy as a function of probe energy from the oscillator for both normal mode and Q-switch mode operations. As the probe energy increases, the laser amplifiers extract more energy from the gain medium without any sign of saturation. It is also observed, not shown in the figure, that the second amplifier always extracts more energy than the first amplifier. This indicates that the amplifiers are operated in a non-saturation regime. Consequently, the amplifier

efficiency could be further improved with higher probe energy.

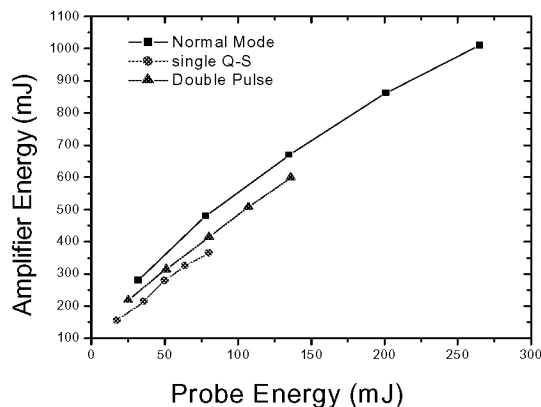


Fig.3 Amplifier output as function of probe energy

Figure 4 shows the amplifier performance for normal mode, Q-switched single pulse and double pulse operation as a function of pump energy. The amplifier reaches transparency at a pump energy of  $\sim 6$  J for Q-switch operations. However, it requires more than 7 J of pump energy to reach transparency for normal mode operation. As the pump energy increases, the probe beam energy is amplified efficiently. For normal mode operation, a total of 1.01 J output energy is achieved with pump energy of 13.3 J.

Double pulse operation improves the overall efficiency of the laser system. At single Q-switch pulse operation, 365 mJ is obtained; representing an optical-to-optical efficiency of 2.8% and only 38% of the normal mode energy has been utilized for the single pulse Q-switch operation. In double pulse operation, however, 600 mJ of energy has been achieved. The optical-to-optical efficiency of the amplifier is increased to 4.5%, and 61% of the normal mode energy has been converted into useful Q-switched output. This represents a 61% laser efficiency improvement in double pulsed operation compared to single pulse operation. It is clear from Fig. 2 that, even for high pump energy, the cumulative gain is still in a non-saturating regime and is expected to increase linearly with an increase in pump energy. Higher pump and probe energies will allow more efficient extraction in a near-saturation regime and still improve the cumulative gain.

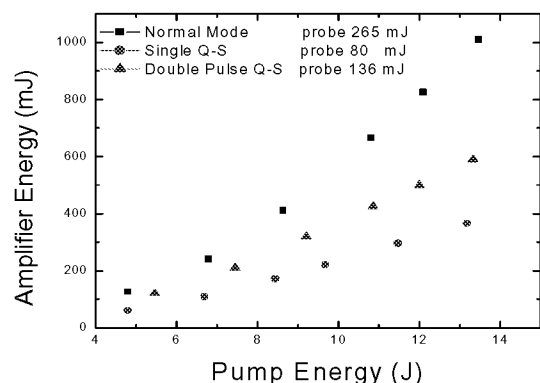


Fig. 4 Amplifier energy as function of incident pump energy

## CONCLUSION

In conclusion, we have described the development of a diode-pumped, double pulsed 2- $\mu$ m Ho laser amplifier. A total output energy of 600 mJ per pulse pair under Q-switch operation is achieved with optical to optical efficiency. Compared to the previous result in which four amplifiers were used, the same output energy has been obtained with only two amplifiers, that represents a factor of two improvement in the system efficiency. This highly efficient laser amplifier can be an ideal lidar transmitter for multiple DIAL applications.

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